Fermi National Accelerator Laboratory

FERMILAB-Conf-98/010-E

Top Quark Physics and Searches for New Phenomena at the Tevatron

Raymond E. Hall

University of California, Irvine
Irvine, California 92697

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

January 1998

Published Proceedings of the *XXVII International Symposium on Multiparticle Dynamics*, Frascati, Italy, September 8-12, 1997

Disclaimer

Distribution

Top Quark Physics and Searches for New Phenomena at the Tevatron

Raymond E. Hall
University of California, Irvine,
Department of Physics and Astronomy, Irvine, California 92697

The CDF and DØ collaborations each have collected over 110pb^{-1} of data. The following article will describe near final results from two currently topical analyses: results from top quark physics and searches for first generation leptoquarks (LQ), using the entire statistics of these large data sets. After careful selection, both collaborations have collected top quark data samples consisting of several dozen events each. From these events both experiments have measured the top quark mass and pair production cross section in a variety of decay channels, including the so-called dilepton, lepton plus jets, and all jets channels. The combined top quark mass from both experiments in the lepton plus jets channels is $m_t = 175.6 \pm 5.5\text{GeV}/c^2$. CDF and DØ have also performed optimized searches for the pair production of first generation leptoquarks. No candidate events were found. Combining the results from the ee+jets, $e\nu$+jets, and $\nu\nu$+jets channels both experiments set 95% confidence level (CL) upper limits on the LQ pair production cross section as a function of mass and of β, the branching fraction to a charged lepton.

1. Top Quark Physics

The discovery of the top quark by the CDF and DØ collaborations in 1995 [1,2] ended a long search following the 1977 discovery of the b quark. Since, the integrated luminosity available to the two collaborations has approximately doubled, to about 110 pb^{-1}. The sophistication of the top quark analyses by the two experiments has increased as well.

In the Standard Model (SM) the top quark completes the third fermion generation. A measure of the top quark pair production cross section is of interest as a test of QCD predictions. A deviation from these predictions could indicate non-standard production or decay modes. Calculations of the cross section is necessarily given as a funtion of top mass, m_{top}, which we also measure.

It turns out that the top quark has a large mass that can be determined to greater fractional precision than is possible for the lighter quarks, which decay after they form hadrons. Also, since m_{top} is large it controls the strength of quark-loop corrections to tree-level relations among electroweak parameters. If these parameters and m_{top} are measured with some precision, the Standard Model Higgs boson mass can be constrained.

At the Tevatron, top quarks are pair produced in $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions. In the Standard Model, top quarks decay 100% of the time to a W boson and a b quark, with subsequent decay of the W boson into either a charged lepton and a neutrino, or a quark-antiquark pair. Top quark signatures are classified on the basis of the decay of the two W bosons into the dilepton (ee, $e\mu$, and $\mu\mu$), lepton (e or μ) plus jets, and all jets decay channels.

1.1. m_{top} in the Lepton plus Jets Channel

The lepton plus jets channel has produced the most precise measurement of the top quark mass to date [3,4]. The analysis method used by the two experiments is very similar. Events are required to have one charged lepton (e or μ), four or more jets and missing E_T. Both experiments make use of information that identifies or "tags" certain jets as b quark jets. Jets can be b-tagged by means of a displaced vertex in the SVX (CDF) or by the presence of a soft lepton near the jet (CDF and DØ). For untagged events, DØ uses a multivariate event shape requirement to improve the signal to background ratio. Events are reconstructed using the four leading jets with a 2C fit to the top quark pair hypothesis. A top quark mass likelihood function is derived from the observed distribution of reconstructed masses using

Table 1
Top quark mass results. If two errors are specified, the first is statistical and the second is systematic.

Exp.	Method	m_{top} (GeV/c^2)
CDF	ℓ + jets	$176.8 \pm 4.4 \pm 4.8$
	$\ell\ell$ (E_b)	$159^{+24}_{-22} \pm 17$
	$\ell\ell$ ($m_{\ell b}$)	$162 \pm 21 \pm 7$
	all jets	$186 \pm 10 \pm 12$
DØ	ℓ + jets	$173.3 \pm 5.6 \pm 6.2$
	$\ell\ell$	$168.4 \pm 12.3 \pm 3.7$
	$\ell\ell$, $\ell + jets$	$172.0 \pm 5.1 \pm 5.5$
CDF+DØ	$\ell + jets$	175.6 ± 5.5

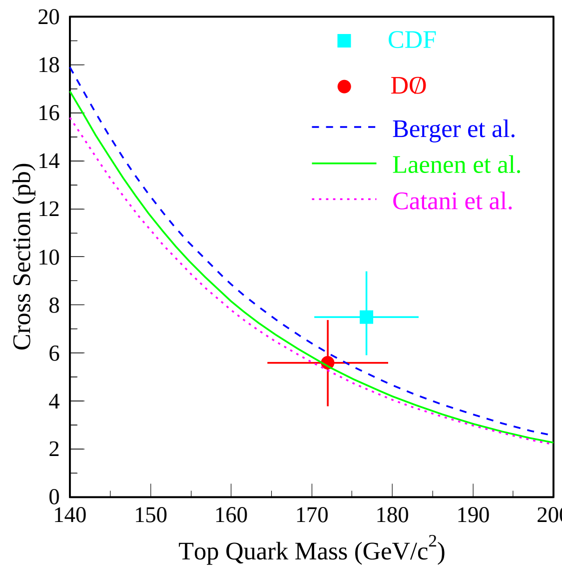

Figure 1. Top quark cross section vs. mass. Error bars represent systematic and statistical errors in quadrature.

signal and background "templates." A template is the expected distrubution of reconstructed top quark mass for background events or top quark events of a particular assumed mass. The results from the lepton plus jets channels are summarized in Table 1, along with all other top quark mass results.

1.2. m_{top} in the Dilepton Channel

Dilepton event selection requires two charged leptons (e or μ), two or more jets, and missing E_T. The dilepton channel differs from the lepton plus jets channel in that there is not enough kinematic information to reconstruct the event. Therefore, the experiments have resorted to using mass estimators other than the reconstructed mass. In principle, any quantity that is correlated with the top quark mass can be used as an estimator. In all cases, the same template technique that was used for the lepton plus jets mass analysis is used to calculate a top quark mass likelihood in the dilepton mass analysis.

This independent measurement is important as a direct test of the hypothesis that the excess of events over background in both the lepton + jets and dilepton channels are due to top quark pair production.

The two experiments use different quantities as the top quark mass estimators. CDF has done two analyses using the b quark jet energy (E_b), and the lepton-b invariant mass ($m_{\ell b}$) as the mass estimator [3]. DØ uses a "weight curve" method, in which a weight is derived as a function of an assumed top quark mass that describes how likely each candidate event is to have come from a particular mass top quark. A separate weight curve is derived for each candidate event. In principle, the whole curve is the mass estimator, although DØ actually uses only four numbers extracted from the curve [5]. DØ has also combined its dilepton and lepton plus jets mass measurements into a single top quark mass measurement. The results of the dilepton mass analyses can be found in Table 1.

1.3. m_{top} in the All Jets Channel

CDF has obtained a top quark mass measurement in the all jets channel [6]. The event selection for the all jets channel consists of six or more jets, an SVX b-tag, plus further event shape requirements. The event sample consists of 136 events with an expected background of 108±9. This measurement uses the reconstructed top quark mass based on a 3C fit to the top quark pair hypothesis as its mass estimator, with likelihood derived using the same template method that is used for other top quark mass measurements. The all jets top quark mass result is shown

Table 2
Top quark cross section results from CDF ($m_t = 175$ GeV/c^2) and DØ ($m_t = 172$ GeV/c^2).

Exp.	Channel	$\epsilon \times BR$ (%)	Data	Background	$\sigma_{t\bar{t}}$ (pb)
CDF	$\ell\ell$	0.74 ± 0.08	9	2.1 ± 0.4	$8.5^{+4.4}_{-3.4}$
	ℓ + jets (SVX b-tag)	3.5 ± 0.7	34	8.0 ± 1.4	$6.8^{+2.3}_{-1.8}$
	ℓ + jets (soft lepton b-tag)	1.7 ± 0.3	40	24.3 ± 3.5	$8.0^{+4.4}_{-3.6}$
	Combined leptonic		83	33.4	$7.5^{+1.9}_{-1.6}$
CDF	All jets (single SVX b-tag)	4.4 ± 0.9	187	142 ± 12	$9.6^{+4.4}_{-3.6}$
	All jets (double SVX b-tag)	3.0 ± 0.9	157	120 ± 18	$11.5^{+7.7}_{-7.0}$
	Combined all jets				$10.1^{+4.5}_{-3.6}$
CDF	$\ell\tau$	0.12 ± 0.014	4	2.0 ± 0.4	15.6^{+19}_{-13}
DØ	$\ell\ell$, $e\nu$	0.91 ± 0.17	9	2.6 ± 0.6	6.4 ± 3.4
	ℓ + jets (no b-tag)	2.27 ± 0.46	19	8.7 ± 1.7	4.1 ± 2.1
	ℓ + jets (soft μ b-tag)	0.96 ± 0.15	11	2.4 ± 0.5	8.3 ± 3.6
	Combined leptonic	4.14 ± 0.69	39	13.7 ± 2.2	5.6 ± 1.8
DØ	All jets (single soft μ b-tag)	1.8 ± 0.4	44	25.3 ± 3.1	7.9 ± 3.5

in Table 1.

1.4. $t\bar{t}$ Production Cross Section

Both experiments have measured the top quark production cross section using a variety of channels. The main results quoted by both experiments are based on channels that contain at least one charged lepton (e or μ), basically the dilepton and lepton plus jets channels described above [7,8]. Both experiments have also measured the top quark cross section using the all jets channel [6,9]. Other channels are the $\ell\tau$ (e or μ plus a hadronically decaying τ) dilepton channel (CDF) [7] and the so-called $e\nu$ channel (DØ) [8], which requires one charged lepton, two or more jets, plus very high missing E_T and $e\nu$ transverse mass.

Event selection sometimes varies slightly between the top quark mass and cross section analyses. For example, both experiments only require three jets in the lepton plus jets cross section analysis, compared to four in the mass analysis. Cross section results are summarized in Table 2.

1.5. Top Physics Summary

The CDF and DØ top quark mass and cross section results are shown in Fig. 1, together with three theoretical predictions [10]. These top quark mass results together with recent results on the W mass measurement [11] place constraints on the allowed SM Higgs mass. As shown in Fig. 2, the central values of the Tevatron results favor a lighter Higgs mass.

2. First Generation Leptoquark Search

One of the remarkable features of the Standard Model (SM) is the symmetry between quarks and leptons that leads to cancellation of chiral anomalies and renders the SM renormalizable. This symmetry might be explained by a more fundamental theory that relates quarks and leptons. Several extensions [12] of the SM include leptoquarks (LQ): color-triplet bosons which carry both lepton (ℓ) and quark (q) quantum numbers. The masses and coupling strengths of leptoquarks that couple to all three fermion generations are severely constrained by low energy experiments [13] and by HERA [14]. Therefore, only LQ that couple to a single generation can be light enough to be accessible at present accelerators. The excess of events at high Q^2 in e^+p collisions reported [15] by the H1 and ZEUS experiments at HERA, and its possible interpretation [16] as evidence for production of first generation scalar leptoquarks with a mass near 200 GeV/c^2, have stimulated much interest in these particles.

Leptoquarks would be dominantly pair-produced via strong interactions in $p\bar{p}$ collisions,

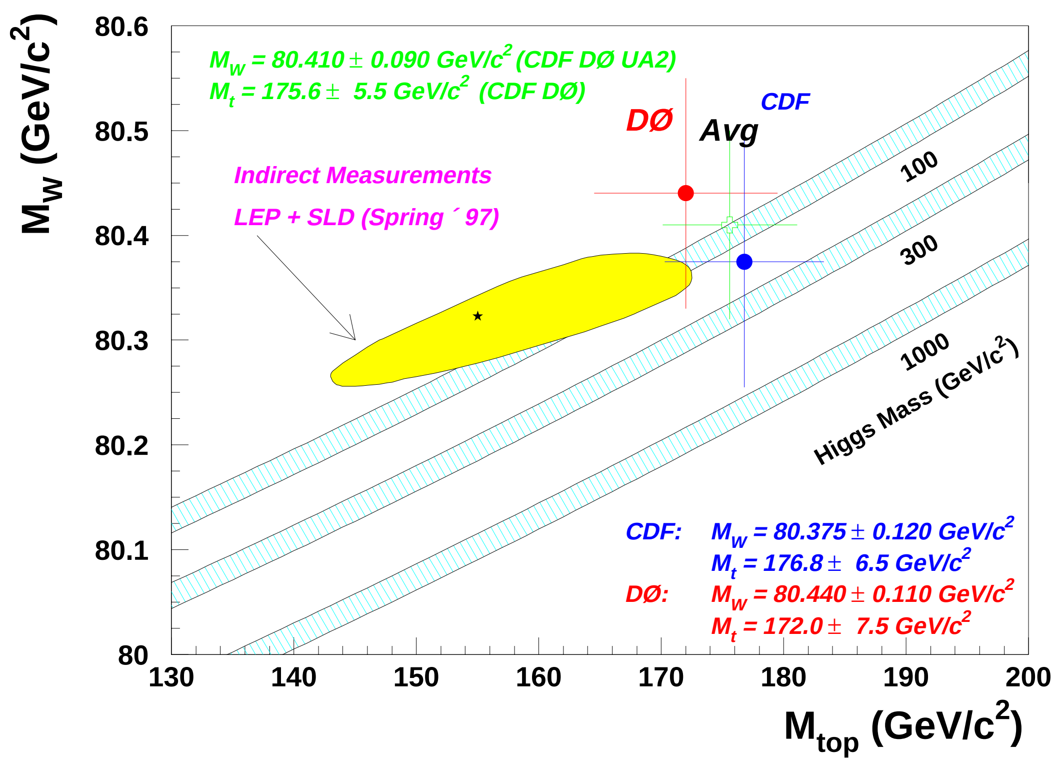

Figure 2. W mass vs. top quark mass from the Tevatron (points) and recent one σ contours from fits to LEP and SLD data. The average Tevatron value is preliminary, awaiting a formal analysis to combine the uncertainty from the two experiments. Errors given are systematic and statistical added in quadrature.

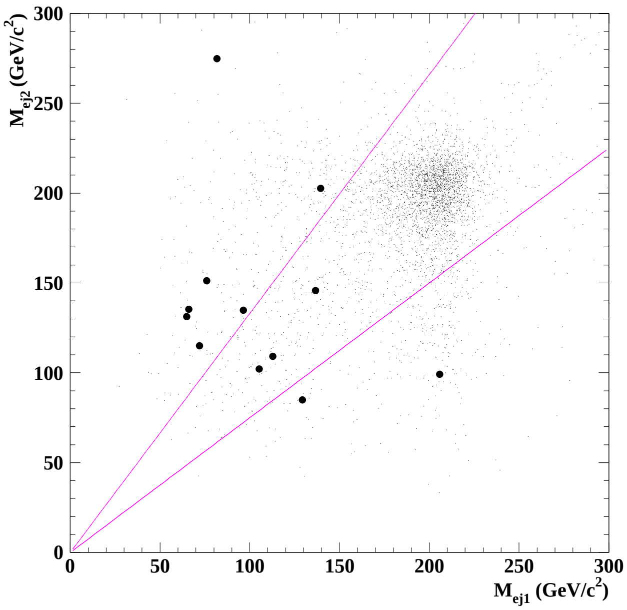

Figure 3. Electron-jet mass correlation on the m_{ej1} *vs.* m_{ej2} plane. Bold points are candidates (see text) and dots are $m_{LQ} = 200$ GeV Monte Carlo.

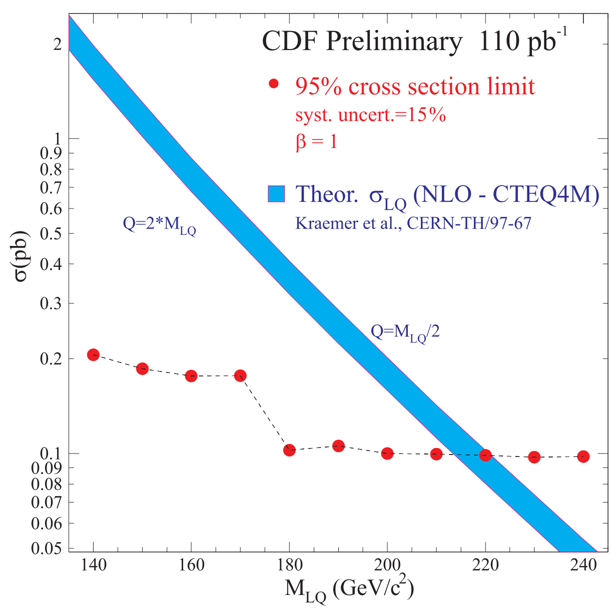

Figure 4. LQ cross section *vs.* mass. For $\beta = 1$ intersection of cross section 95% CL upper limit (points) with NLO theory (band) gives $m_{LQ} >$ 213 GeV at 95% CL.

independently of the unknown LQ–ℓ–q Yukawa coupling. Each leptoquark would subsequently decay into a lepton and a quark. For first generation leptoquarks, this leads to three possible final states: ee+jets, $e\nu$+jets and $\nu\nu$+jets, with rates proportional to β^2, $2\beta(1-\beta)$, and $(1-\beta)^2$, respectively, where β denotes the branching fraction of a leptoquark to an electron and a quark (jet).

CDF and DØ use different techniques in their LQ search strategies. The following discussion will be limited to the $eejj$ channel search from CDF and the $eejj$ and $e\nu jj$ channels from DØ which set the tightest current limits.

2.1. CDF LQ Search: $\beta = 1$

The CDF collaboration uses kinematic selection in conjunction with balancing the reconstructed mass of each ej pair, $m_{ej1} = m_{ej2}$. Selection requirements include: two electrons with $E_T > 25$ GeV, two jets ($E_T^1 > 30$ and $E_T^2 > 15$ GeV, and an invariant mass requirement on the dielectron pair, $76 < M_{ee} < 106$ GeV, to reduce the major background of Z decays. Further, the scalar sum of the two electrons' E_T and the scalar sum of the jets' E_T must be greater than 70 GeV each to remove continuum Drell-Yan background. The events passing these criteria, from a 110 pb^{-1} data sample, are shown on the m_{ej1} *vs.* m_{ej2} plane in Fig. 3.

The final LQ candidates (for a given LQ mass, m_{LQ}) are selected by choosing events with the mean m_{ej} of the pair to be within 3σ of m_{LQ}. The cross section limit obtained (Fig. 4) uses signal acceptence calculations from event sets generated using the PYTHIA Monte Carlo generator. Comparison with theory [17] gives $m_{LQ} > 210$ GeV at 95% CL.

2.2. LQ limits from DØ

The DØ Collaboration uses loose initial selection and formal optimization of kinematic selection using a Random Grid Search [22] and using neural net [23] techniques. Both techniques yield similar results. DØ uses similar but less restrictive initial kinematic selection; two electrons $E_T > 20$ GeV, two jets $E_T > 15$ GeV, and an invariant mass cut on the dielectron pair of

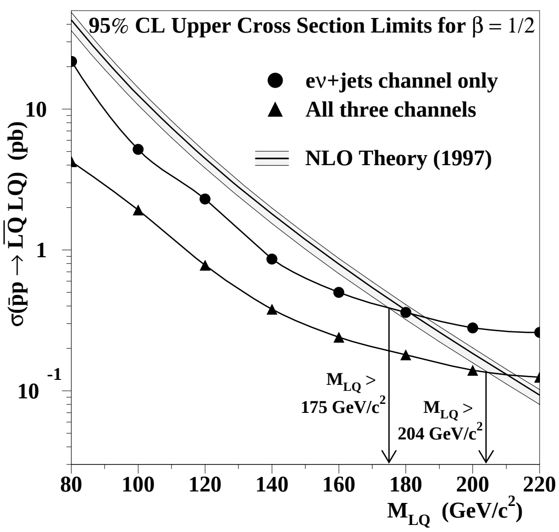

Figure 5. Measured 95% CL upper limits on the leptoquark pair production cross section (see text) in the $e\nu$ + jets channel (circles) and all three channels combined (triangles) for $\beta = \frac{1}{2}$. Also shown are the NLO calculations of Ref. [17] where the central line corresponds to $\mu = m_{LQ}$, and the lower and upper lines to $\mu = 2m_{LQ}$ and $\mu = \frac{1}{2}m_{LQ}$, respectively.

$82 < m_{ee} < 100$GeV. This leaves 101 events out of 123 pb^{-1} of data. The optimization consists of finding the most sensitive discriminator for LQ selection using the two techniques above, and placing a cut on this discriminator to maxmize the expected signal while constraining the background to a fixed level (0.4 events).

Investigation of more than 40 combinations of variables found that the discriminator S_T defined as the scalar sum of the E_T of both electrons and all jets with $E_T > 15$ GeV to be most sensitive. Final selection set $S_T = 350$ GeV, giving no candidate events on a background of 0.44 ± 0.06 events and a final efficiency of 16 to 36% for m_{LQ} = 160 to 250 GeV. Comparison with theory [17] yields $M_{LQ} > 225$ GeV for $\beta = 1$ at 95% CL [19].

The LQ search with $\beta = 0.5$ opens up the $e\nu jj$ channel (50% of decays) as well as the $eejj$ and $e\nu jj$ channels (25% of decays each). This search includes the $eejj$ analysis above folded with another search for a single electron plus missing E_T topology. The analysis is similar in design to the $eejj$ search, but here the backgrounds are $t\bar{t}$ and $W + 2$ jet production. The initial selection is the same except for the substitution of missing $E_T > 30$GeV in place of the second electron, and raising the jet E_T requirment to 20GeV. In addition, the transverse mass of the $e\nu$ pair must exceed 110 GeV to minimize the background from W production. Final selection is based on a neural net discriminator, which uses two optimized variables as input: S_T and the smallest difference bewteen the assumed LQ mass and M_{eji}. After this final cut, no candidate events survive, on a background estimate of 0.29 ± 0.25 to 0.61 ± 0.27 events for m_{LQ} from 80 to 200GeV. Using Bayesian statistics, we obtain a 95% CL upper limit to the LQ pair production as a function of LQ mass (Fig. 5). For the $e\nu$ channel alone comparison with theory sets a 95% CL lower limit on the LQ mass of 175 GeV.

An analysis of the $\nu\nu$ + jets channel is accomplished by making use of our published search (with $\int Ldt \approx 7.4$ pb^{-1}) for the supersymmetric partner of the top quark [20]. Three events survive the selection criteria ($\not{E}_T > 40$ GeV, 2 jets with $E_T^j > 30$ GeV, and no isolated electrons or muons) consistent with the estimated background of 3.5 ± 1.2 events, mainly from W/Z+jets production with efficiencies of 1.1 to 3.9% for m_{LQ}= 60 to 100 GeV. This analysis yields the limit m_{LQ} >79 GeV at the 95% CL for β =0.

Combining the ee+jets, $e\nu$+jets, and $\nu\nu$+jets channels, DØ calculates 95% CL upper limits on the LQ pair production cross section as a function of LQ mass for various values of β [21]. These cross section limits for $\beta = \frac{1}{2}$ (shown in Fig. 5), when compared with NLO theory, yield a 95% CL lower limit on the LQ mass of 204 GeV. The lower limits on the LQ mass derived as a function of β, from all three channels combined, as well as from the individual channels, are shown in Fig. 6.

2.3. Conclusions

In conclusion the CDF and DØ Collaborations have both searched for first generation scalar leptoquarks. The Tevatron results limit the interpretation of the HERA high Q^2 event excess. For example, the DØ results exclude (at the 95% CL)

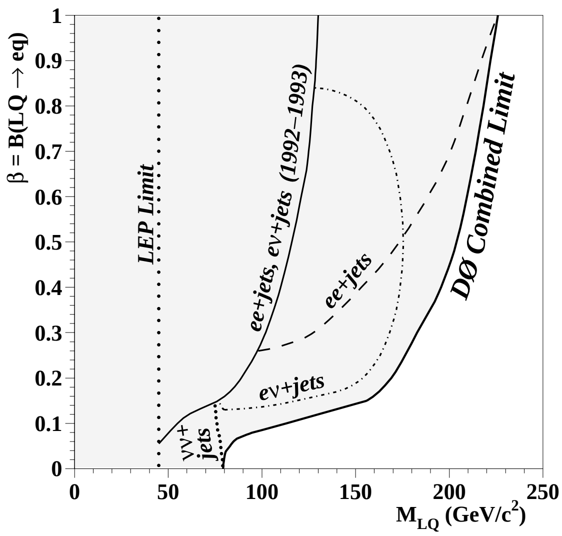

Figure 6. Lower limits on the first generation scalar leptoquark mass as a function of β, based on searches in all three possible decay channels for LQ pairs. Limits from LEP [24] and from our previous analysis [18] of 1992–93 data are also shown. The shaded area is excluded at 95% CL.

the interpretation of the HERA high Q^2 event excess as s-channel scalar LQ production with LQ mass below 200 GeV/c^2 for values of $\beta > 0.4$, and significantly restrict new LQ models containing additional fermions [25].

REFERENCES

1. CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett., **74**, 2626 (1995).
2. DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett., **74**, 2632 (1995).
3. J. Antoš for the CDF Collaboration, Fermilab-Pub-97/058-E.
4. DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett., **79**, 1197 (1997).
5. DØ Collaboration, B. Abbott *et al.*, Fermilab-Pub-97/172-E.
6. CDF Collaboration, F. Abe *et al.*, Fermilab-Pub-97/075-E.
7. M. Gallinaro for the CDF Collaboration, Fermilab-Conf-97/004-E;
8. DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett., **79**, 1203 (1997).
9. N. Amos for the DØ Collaboration, presented at 12th Hadron Collider Physics Symposium, Stony Brook, New York, June 5–11, 1997.
10. E. Laenen, J. Smith, and W. van Neerven, Phys. Lett. **321B**, 254 (1994); E. Berger and H. Contopanagos, Phys. Lett. **361B**, 115 (1995) and Phys. Rev. D **54**, 3085 (1996); S. Catani, M.L. Mangano, P. Nason, and L. Trentadue, Phys. Lett. **378B**, 329 (1996).
11. S. Rajagopalan, Production and Properties of Vector Bosons Observed at the Tevatron, in these proceedings.
12. J. C. Pati and A. Salam, Phys. Rev. D **19**, 275 (1974); H. Georgi and S. Glashow, Phys. Rev. Lett.**32**, 438 (1974); also, see J. L. Hewett and T. G. Rizzo, Phys. Rep.**183**, 193 (1989).
13. See e.g., M. Leurer, Phys. Rev. D **49**, 333 (1994)
14. H1 Collaboration, S. Aid *et al.*, Phys. Lett. **B369**, 173 (1996); ZEUS Collaboration, M. Derrick *et al.*, Z. Phys. **C73**, 613 (1997).
15. H1 Collaboration, C. Adloff *et al.*, Z. Phys. **C74**, 191 (1997); ZEUS Collaboration, J. Breitweg *et al.*, Z. Phys. **C74**, 207 (1997).
16. J. L. Hewett and T. G. Rizzo, to appear in Phys. Rev. D **56**, 5709 (1997).
17. M. Krämer, T. Plehn, M. Spira, and P.M. Zerwas, Phys. Rev. Lett., **79**, 341 (1997).
18. DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **72**, 965 (1994).
19. DØ Collaboration, B. Abbott *et al.*, Phys. Rev. Lett. **79** 4327 (1997).
20. DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **76**, 2222 (1996).
21. DØ Collaboration, B. Abbott *et al.*, to appear in Phys. Rev. Lett. hep-ex/9710032.
22. N. Amos *et al.,* Proceedings of the International Conference on Computing in High Energy Physics '95, p.215.
23. P.C. Bhat, in *Proceedings of the* 10^{th} *Topical Workshop on Proton-Antiproton Collider Physics*, p. 308 (AIP Press, 1995); C. Peterson *et al.*,, Comp. Phys. Comm. **81**, 185 (1994). We used JETNET version 3.0.
24. See e.g., P. Mättig, preprint CERN–PPE/96-187.
25. J.L. Hewett and T.G. Rizzo, hep-ph/9708419, submitted to Phys. Rev.D.